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THEORY AND OPERATION OF A TIME-INTEGRATING, CONTINUOUS, RADON DAUGHTER MONITOR

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ELLIOT LAKE LABORATORY

SEPTEMBER 1983

FEB 07 1984

MICROMEDIA

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MINERALS RESEARCH PROGRAM
MINING RESEARCH LABORATORIES
DIVISION REPORT MRP/MRL 83-87 (TR)

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by

J. Bigu*, R. Kaldenbach+, and M. Grenier**

ABSTRACT

An environmental radon daughter monitor has been designed and tested under laboratory controlled conditions in a large radon/thoron test facility (26 m^3) and in an underground uranium mine. The monitor operates on continuous sampling and time integrating principles. It has been tested under constant and rapidly fluctuating radiation conditions. Experimental data obtained with the monitor were compared with data obtained by conventional grab-sampling and with other automated radiation instrumentation. The Working Levels used in the tests ranged from less than 0.01 to approximately 10. Measurements in the radon/thoron test facility were conducted preferentially at low relative humidity and low aerosol concentration (1×10^3 to 2×10^3 cm^{-3}) to study plate-out effects in the sampling head. Good agreement (within about 10%) was found between the monitor, conventional grab-sampling and other automated radiation instrumentation previously tested at our laboratories. Plate-out and contamination effects on the instrument detector and sampling head have been observed when tested with thoron/thoron daughter atmospheres. The response of the monitor to rapidly fluctuating radiation environments is somewhat limited showing a time lag whose magnitude depends on the decay products (i.e., radon daughters or thoron daughters) and the rate of change of the radiation level. The time lag observed is in accordance with theoretical predictions. Although the monitor was originally designed for radon daughters, it can equally be used in thoron daughter atmospheres and radon daughter/thoron daughter mixtures such as those encountered in some Canadian uranium mines. An analytical procedure is outlined to allow the calculation of Working Levels in radon daughter atmospheres and thoron daughter atmospheres, and in radon daughter/thoron daughter atmospheric mixtures from the monitor α-count rate. The memory capability of the monitor should make it quite useful and flexible in underground and surface environments in the uranium mining industry.

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PRINCIPES ET FONCTIONNEMENT D'UN MONITEUR CONTINU DES DESCENDANTS DU RADON À INTÉGRATION TEMPORELLE

par

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RÉSUMÉ

Un moniteur des descendants du radon a été conçu et mis à l'essai dans des conditions de laboratoire contrôlées dans une chambre d'essai au radon/thoron de grandes dimensions (26 m^3) et dans une mine d'uranium souterraine. Le moniteur est à échantillonnage continu et à intégration temporelle. Les essais ont été faits en présence de rayonnement constant et de rayonnement fluctuant rapidement. Les données expérimentales obtenues ont été comparées à des données obtenues au moyen d'appareils à échantillonnage aléatoire discontinu et d'autres appareils automatiques de contrôle du rayonnement. Les niveaux de travail utilisés pour les essais se situaient entre un peu moins de 0,01 et 10 environ. Les mesures prises dans la chambre d'essai l'ont été de préférence à faible humidité relative et à faible concentration en aérosols (de 1 x 10^3 à 2 x 10^3 cm^{-3}) afin qu'il soit possible d'étudier les effets de la fixation dans la tête d'échantillonnage. Les résultats produits par le moniteur, par un échantilloneur aléatoire classique et par d'autres appareils automatiques de contrôle du rayonnement antérieurement mis à l'épreuve dans nos laboratoires concordaient assez bien (à près de 10% environ). Il a été possible d'observer les effets de la fixation et de la contamination sur le fonctionnement du détecteur et de la tête d'échantillonnage du moniteur dans des atmosphères de descendants du radon et du thoron. La réponse du moniteur au rayonnement fluctuant rapidement est quelque peu limitée et présente un temps mort dont la durée dépend de la nature des produits de filiation (descendants du radon ou descendants du thoron) ainsi que de la vitesse à laquelle varie l'intensité du rayonnement. Le temps mort observé concorde avec les prévisions théoriques. Bien qu'il

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ait été conçu à l'origine pour les descendants du radon, le moniteur peut tout aussi bien être utilisé dans des atmosphères de descendants du thoron et dans des atmosphères mixtes de descendants du radon et du thoron, comme celles qui existent dans certaines mines d'uranium canadiennes. On présente dans ce document une méthode de calcul des niveaux de travail dans les atmosphères de descendants du radon et de descendants du thoron ainsi que dans les atmosphères mixtes à partir du taux de comptage alpha. Grâce à sa mémoire, le moniteur devrait pouvoir être employé utilement et avec souplesse sous terre et en surface dans l'industrie minière de l'uranium.

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INTRODUCTION

Radiation environments pose potential hazards to human health, hence, the need for adequate monitoring of radiation levels. Radiation monitoring is also important for engineering purposes such as the maintenance of reliable air quality control in working areas.

Monitoring of radiation levels is accomplished essentially by two different methods: a 'discrete' one normally known as grab-sampling, and a continuous method, generally referred to as continuous monitoring. Grab-sampling is conceptually simple and relatively inexpensive from the instrumentation point of view, but usually requires a great deal of manual operation which severely limits its capabilities. Continuous monitoring is considerably more complex, instrumentally and analytically, but the automated nature of the sampling and the analysis processes makes it clearly preferable when large amounts of data are required, as is the case in a variety of engineering, industrial and research applications and for health physics purposes.

A number of instruments have been developed in recent years to monitor radiation levels of the decay products of radon and thoron. However, although the field of radiation instrumentation has proliferated, there is a need for an automated area monitoring instrument with memory storage capabilities suitable for unattended monitoring for extended periods of time. Such an instrument could be used extensively in underground environments for air quality monitoring purposes. An instrument of this kind, operating on time-integrating principles, is available and has been tested under controlled laboratory conditions in a large radon/thoron room designed for calibration pusposes and in an underground uranium mine. The instrument has been designed and built by EDA Instruments (Toronto) and is commercially available under the name WLM-300.

This paper presents data pertaining to a technical evaluation of the WLM-300, and is a summary of previous work (1 to 3), and on-going work carried out in conjunction with a program aimed at a long-term monitoring of radon(thoron) daughter levels in underground environments.

DESCRIPTION OF THE APPARATUS

The EDA WLM-300 basically consists of a sampling-detection system, a memory unit to store data, and read-out and print-out capabilities. The instrument operates by sampling air in a continuous fashion. Decay products are deposited on a sampling filter facing the detector and the α-count is integrated in a manner described below. The instrument has been designed, according to the manufacturer's specifications, to be dust-proof, moisture-proof and shock-proof.

The detection-sampling 'head' consists of a sample holder housing a filter (Millipore 0.8 μm AA) supported by a fine stainless steel mesh screen. A ruggedized silicon-barrier detector (450 mm^2 active area) faces the active side of the filter. The detector-filter separation is about 3.2 mm.

The front-end electronic circuitry of the detector has a voltage threshold corresponding to an α-energy of about 2 MeV to eliminate contributions from electronic noise and β-radiation. Alpha-particles in the 2 MeV to 10 MeV energy range are detected and counted. Although the apparatus has no pulse height analysis capabilities, it is provided with an output jack to enable interfacing with an external multichannel analyzer (MCA) for pulse height analysis.

The filter-detector holder is cylindrically shaped and is made of a plastic material (Teflon) consisting of an upper and a lower part. In the normal operating mode, the upper part is fitted, leak-free, by means of an

'O'-ring, to the lower part by screwing the former into the latter. The upper part has four exhaust holes leading to the inlet of a small self-regulated sampling pump (1 L/min) which draws air in and passes it through the sampling filter facing the detector. The lower part has a circular inset where the detector is located about 1 mm below two inlet slits of rectangular cross-section, approximately 9 mm x 2 mm and symmetrically oriented at 180° from each other, permitting air to be sampled to pass through the filter facing the detector.

The detection-sampling head is located in a re-entrant 'cavity' built on one side of the instrument case. The inlet access slits, detector and sampling filter are located at an approximate depth of 15 mm from the surface of the case.

The instrument has a liquid crystal display (LCD) which displays the α-count rate internally obtained by dividing the total number of α-counts by the total sampling time, and the WL obtained from the above α-count rate and a given numerical conversion factor.

A memory unit enables data storage which can be retrieved later by an external printer. Data are gathered every 6 min or 60 min. The memory capacity is 4.1 days if data are gathered every 6 min, or 41 days if data are gathered every 60 min.

The data stored can be retrieved in the following forms:

a) As differential α-count at any given time. This is the α-count obtained by subtracting the total α-count stored up to the last (previous) count, from the total α-count up to this time;

b) As total α-count. This is the total, accumulated, α-count up to the time data are retrieved;

c) As differential WL. This is calculated from item (a) and a given numerical

conversion factor; and

d) As a time integrated WL which is calculated from the integral, total α-count obtained, the total counting time, and the same conversion factor as that indicated (see above and item c).

For simplicity the WLM-300 will be referred to hereafter as the monitor.

THEORETICAL BACKGROUND

The instrument operates by sampling air in a continuous fashion and integrating the α-count as indicated above.

The WL can be determined by multiplying the α-count rate (i.e., counts per minute, cpm, as determined from the total α-count during a given sampling time interval, namely 6 min or 60 min) under steady-state conditions, by a conversion factor. (This conversion factor although it has been calculated theoretically, see below and Tables A-1 and A-2, should be determined experimentally because of plate-out phenomena in the sampling head of the instrument and other effects (1,2).) Notice that this terminology is used here to indicate the minimum sampling time for which the rates of growth and decay of decay products on the sampling filter are the same, assuming that the flow rate and the concentrations of the decay products in air remain constant during the time of sampling.

If the sampling pump flow rate, say Q, the counting efficiency of the detector, say ε, and the concentrations of the radon and/or thoron decay products are known, one can calculate the theoretically expected integrated α-count after a given sampling time T_s. Conversely, if the integrated α-counts at different T_s are known by experimental means, and Q and ε are also known, the decay product concentrations, and their corresponding WL, can be calculated.

The rate of growth of activity on the sampling filter during sampling

is given by the following expression:

$$\frac{dA_m}{dt} = C_m Q + \lambda_m A_{m-1} - \lambda_m A_m \qquad \text{Eq 1}$$

where, A_m and A_{m-1} are the activities of the m-th and (m-1)-th members of the radioactive decay chain on the filter (pCi or Bq), respectively;

C_m is the atmospheric concentration of the m-th member of the radioactive decay chain (pCi/L or Bq/L);

λ_m is the decay constant of the m-th member of the radioactive decay chain (min^{-1});

Q is the instrument (monitor) sampling rate (L/min).

The activities on the filter at time T_s after the beginning of sampling are obtained by integrating Equation 1 for each radionuclide of interest. The total activities accumulated in the filter during a sampling time T_{s1} to T_{s2} (where $T_{s2} > T_{s1}$) are obtained by integrating the expressions for the activities over the sampling period. Using the subindices i, j and k to denote, respectively, RaA or ThA, RaB or ThB and RaC or ThC, and the symbols $A_i(T_s)$, $A_j(T_s)$ and $A_k(T_s)$ to denote the activity of i, j, or k at a time T_s, respectively, it can be shown (see Bigu (4)):

$$IA_iS = \int_{T_{s1}}^{T_{s2}} A_i(T_s)\, dT_s = C_i Q \tau_i F_i \qquad \text{Eq 2}$$

$$IA_jS = \int_{T_{s1}}^{T_{s2}} A_j(T_s)\, dT_s = Q\left[C_j\tau_jF_j + C_i\left(\frac{\tau_i^2F_i}{\tau_i-\tau_j} + \frac{\tau_i\tau_jF_j}{\tau_j-\tau_i}\right)\right] \qquad \text{Eq 3}$$

and

$$IA_kS = \int_{T_{s1}}^{T_{s2}} A_k(T_s)\, dT_s = Q\left[C_k\tau_kF_k + C_j\left(\frac{\tau_j^2F_j}{\tau_j-\tau_k} + \frac{\tau_j\tau_kF_k}{\tau_k-\tau_j}\right) + C_i\left(\frac{\tau_i^3F_i}{(\tau_i-\tau_j)(\tau_i-\tau_k)} + \frac{\tau_i\tau_j^2F_j}{(\tau_j-\tau_i)(\tau_j-\tau_k)} + \frac{\tau_i\tau_k^2F_k}{(\tau_k-\tau_i)(\tau_k-\tau_j)}\right)\right] \qquad \text{Eq 4}$$

where, the expressions IA_iS, IA_jS and IA_kS stand for integrated activity during

sampling of radioactive species i, j, and k, respectively. The other symbols stand for the following:

$$\tau_i = 1/\lambda_i,\ \tau_j = 1/\lambda_j \text{ and } \tau_k = 1/\lambda_k$$

$$F_i = (T_{s2} - T_{s1}) + \tau_i \left(e^{-T_{s2}/\tau_i} - e^{-T_{s1}/\tau_i}\right) \quad \text{Eq 5}$$

$$F_j = (T_{s2} - T_{s1}) + \tau_j \left(e^{-T_{s2}/\tau_j} - e^{-T_{s1}/\tau_j}\right) \quad \text{Eq 6}$$

$$F_k = (T_{s2} - T_{s1}) + \tau_k \left(e^{-T_{s2}/\tau_k} - e^{-T_{s1}/\tau_k}\right) \quad \text{Eq 7}$$

For simplicity, Equations 2, 3 and 4 have been derived making the following assumptions:

1. the concentration of the radon and thoron progenies in air and the instrument pump flow rate remain constant during the sampling period;
2. the sampling filter is an absolute filter, i.e., all decay products are deposited in the filter; and
3. the detector's counting efficiency is not energy dependent.

The total number of α-counts recorded by the instrument during a given sampling period, say N_α, is given by:

$$N_\alpha = 2.22\ \varepsilon\eta\delta(IA_iS + IA_kS) \quad \text{Eq 8}$$

where, 2.22 is a numerical factor to convert pCi into dpm, i.e., (3.7×10^{10} dps/Ci x (10^{-12} Ci/pCi x (60 sec/min)) = 2.22 dpm/pCi. The symbol $\delta(<1)$ is inserted to take into account plate-out of α-particles in the instrument sampling head. $\eta(<1)$ represents the fraction of α-particles emerging from the filter.

It can be shown (1,2,4) that:

$$\text{cpm(Rn)/WL(Rn)} = C_F(\text{Rn}) \quad \text{Eq 9}$$

$$\text{cpm(Tn)/WL(Tn)} = C_F(\text{Tn}) \quad \text{Eq 10}$$

where, WL(Rn) and WL(Tn) are the radon daughter Working Level and the thoron daughter Working Level, respectively;

cpm(Rn) and cpm(Tn) are the α-counting rates, as determined by the

instrument according to Equation 8, for radon daughter and thoron daughter atmospheres, respectively.

$C_F(Rn)$ and $C_F(Tn)$ are, respectively, constant factors for radon daughters and thoron daughters under steady-state conditions. The conversion factors $C_F(Rn)$ and $C_F(Tn)$ have been calculated theoretically and are given in Appendix A for various daughter products disequilibrium ratios.

Using Equations 9 and 10, WL(Rn) and WL(Tn) can be obtained for radon daughter atmospheres only or thoron daughter atmospheres only, respectively. As the instrument cannot differentiate radon daughter α-particles from thoron daughter α-particles, the determination of WL(Rn and WL(Tn) in radon(thoron) mixtures is more complicated. However, it can be shown that (2):

$$WL(Rn) = \frac{cpm(total)\ (F/\varepsilon)}{C_F(Rn) + C_F(Tn)WLR} \qquad \text{Eq 11}$$

where,

$$WLR = WL(Tn)/WL(Rn) \qquad \text{Eq 12}$$

The quantity cpm(total) represents the total α-count rate given by the instrument. The ratio WLR can be determined by a procedure similar to the Ogden method (5,6) suitably modified by Bigu (4) for instrumentation operating on time-integrating principles.

EXPERIMENTAL PROCEDURE

The monitor has been tested extensively under laboratory controlled conditions in a 3 m^3 radon/thoron box (1) and in a 26 m^3 radon/thoron test facility of the walk-in type (3), both designed for radiation instrumentation calibration purposes. In addition, the monitor has been thoroughly tested in an underground uranium mine (2). Experimental data obtained with the monitor were compared with data obtained by conventional grab-sampling and by two automated Working Level monitors of the grab-sampling type. The Thomas-Tsivoglou, Markov and Kusnetz methods were used in conventional grab-sampling (7 to 10).

The automated Working Level monitors used were the WL-1000C, a radon daughter/thoron daughter grab-sampler manufactured by Pylon Electronic Development (Ottawa) (11) and a semi-continuous radon daughter Working Level Meter manufactured by Harshaw Instruments (U.S.A.) under the commercial name of Radon Daughter Detector Model 101 and Radiation Computer Model 100. The results obtained with the Harshaw instrument have been given elsewhere (12).

The monitor was tested under constant and rapidly fluctuating radiation conditions in order to compare the time response of the monitor with that of conventional grab-sampling by different methods and of other automated systems. Furthermore, the monitor was tested under a variety of environmental conditions including relative humidity (RH) and aerosol concentration.

Data obtained with the first monitor prototype showed substantial daughter products plate-out in the sampling head, i.e., above 40% at low aerosol concentrations (1×10^3 cm^{-3} to 2×10^3 cm^{-3}) and RH (1). These data, and other data (2), led to the design of a new sampling head with much improved plate-out characteristics (3).

In order to study the spectral and plate-out characteristics of the monitor, use was made on several occasions of dry Ra-226 and Th-228 sources of the flow-through type Models Rn-1025 and Th-1025, respectively, manufactured by Pylon Instruments (Ottawa).

EXPERIMENTAL RESULTS AND DISCUSSION

Some of the data obtained with the monitor and by grab-sampling are given in Fig. 1 to 4 and Table 1. Other data have been reported elsewhere (1-4).

Figure 1 shows a comparison of theoretical data with experimental results obtained during the course of an underground test in a uranium mine. The variables cpm(Rn), cpm(Tn) and cpm(Rn+Tn) = cpm(Rn) + cpm(Tn) represent

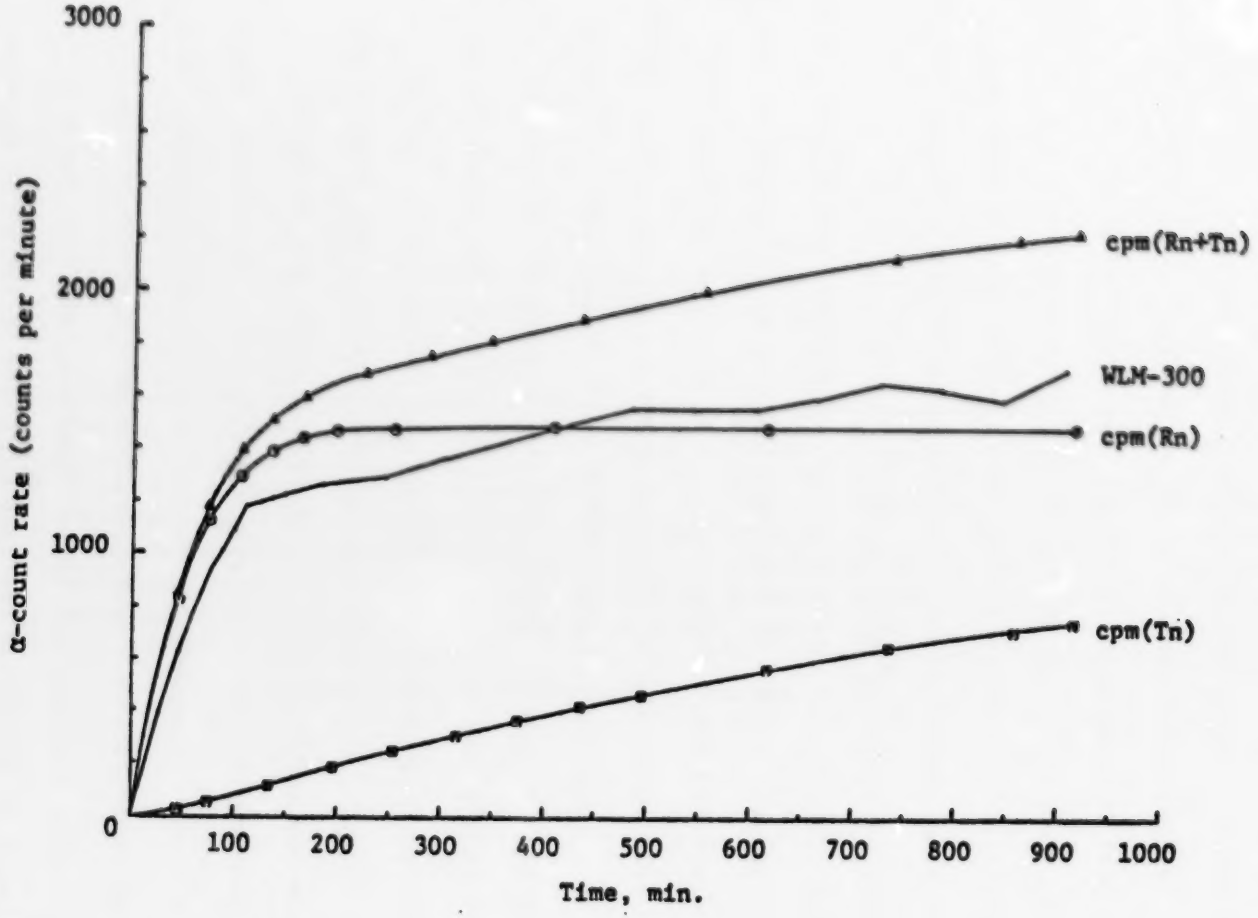

Fig. 1 - Alpha-particle count rate versus time (a) for the WLM-300 (-·-) and (b) theoretical: cpm(Rn) (-⊙-), cpm(Tn) (-▣-) and total (-▲-). Notice that the theoretical cpm has been calculated from experimental data for WL and the C_F-factors as indicated in the text, i.e., cpm(Rn) = $WL(Rn) \times C_F(Rn)$, cpm(Tn) = $WL(Tn) \times C_F(Tn)$ and cpm(Rn+Tn) = cpm(Rn) + cpm(Tn).

the theoretical values for these variables calculated according to the expression given above, Tables A-1 and A-2 (see Appendix A), and using experimental data for the disequilibrium radon(thoron) daughter ratios, and other data from Table 1. Calculations have been performed for Q = 1 L/min and $\varepsilon \simeq 0.2$, as calibrated independently, and assuming $\eta = \delta = 1$. The partial disagreement between the experimental α-count rate given by the monitor (WLM-300) and the theoretical cpm (Rn+Tn) is mainly due to plate-out of decay products in the original monitor's sampling head. Subsequent to these and other tests, the sampling head was modified and its plate-out characteristics have been improved considerably (see Fig. 2).

Figure 2 shows WL(Rn) versus time for the monitor and a microprocessor-controlled 'grab-sampler', Model WL-1000C, manufactured by Pylon Electronics (Ottawa), used for comparison purposes (11). Also shown in the graph are measurements carried out by the conventional Markov method (9). The measurements were conducted in a large (26 m^3) radon/thoron room, where WL(Rn) was varied significantly during the test to investigate the response of the monitor. The aerosol concentration in the room was $\sim 1.0 \times 10^3$ cm^{-3}, a low concentration, purposely maintained to study plate-out effects on the monitor's modified sampling head. Figure 2 shows quite good agreement (within 10%) between the monitor, with the new sampling head, the WL-1000C, previously tested and compared with grab-sampling data, and grab-sampling data. Notice that there is a time lag of about 1 h between the monitor and grab-sampling data. This is to be expected theoretically because the instrument operates on time-integrating principles. (Note: for thoron daughters, the time lag is substantially longer on account of the long half-life of ThB which determines the decay of ThC in the filter.) Thus, in order to correct for time lag, the monitor reading should be accordingly shifted to the left hand side of the time axis.

Table 1 - Summary of grab-sampling data corresponding to 5-shifts of underground testing

Date	WL(Rn)	WL(Tn)	$\frac{WL(Tn)}{WL(Rn)}$	[RaA] (Bq/L)	[RaB] (Bq/L)	[RaC] (Bq/L)	[ThB] (Bq/L)	[ThC] (Bq/L)	1:X:Y*	$\frac{[ThC]}{[ThB]}$
April 30	0.49±0.03	0.41±0.02	0.83±0.1	2.89±0.44	1.93±0.19	1.46±0.07	0.086±0.005	0.041±0.006	1:0.67:0.5	0.47
May 4	0.45±0.03	0.39±0.02	0.87±0.07	3.01±0.44	1.77±0.15	1.28±0.10	-	-	1:0.59:0.42	-
May 5	0.43±0.03	0.43±0.02	0.98±0.13	2.97±0.33	1.71±0.14	1.19±0.16	0.088±0.032	0.037±0.005	1:0.58:0.40	0.42
May 6	0.46±0.02	0.41±0.03	0.88±0.05	3.04±0.13	1.80±0.13	1.30±0.13	0.087±0.01	0.040±0.01	1:0.59:0.43	0.28
May 7	0.49±0.02	0.43±0.01	0.87±0.04	3.22±0.42	1.91±0.10	1.39±0.11	0.125	0.032	1:0.59:0.43	0.25

* 1 = [RaA]/[RaA] ; X = [RaB]/[RaA] ; Y = [RaC]/[RaA]

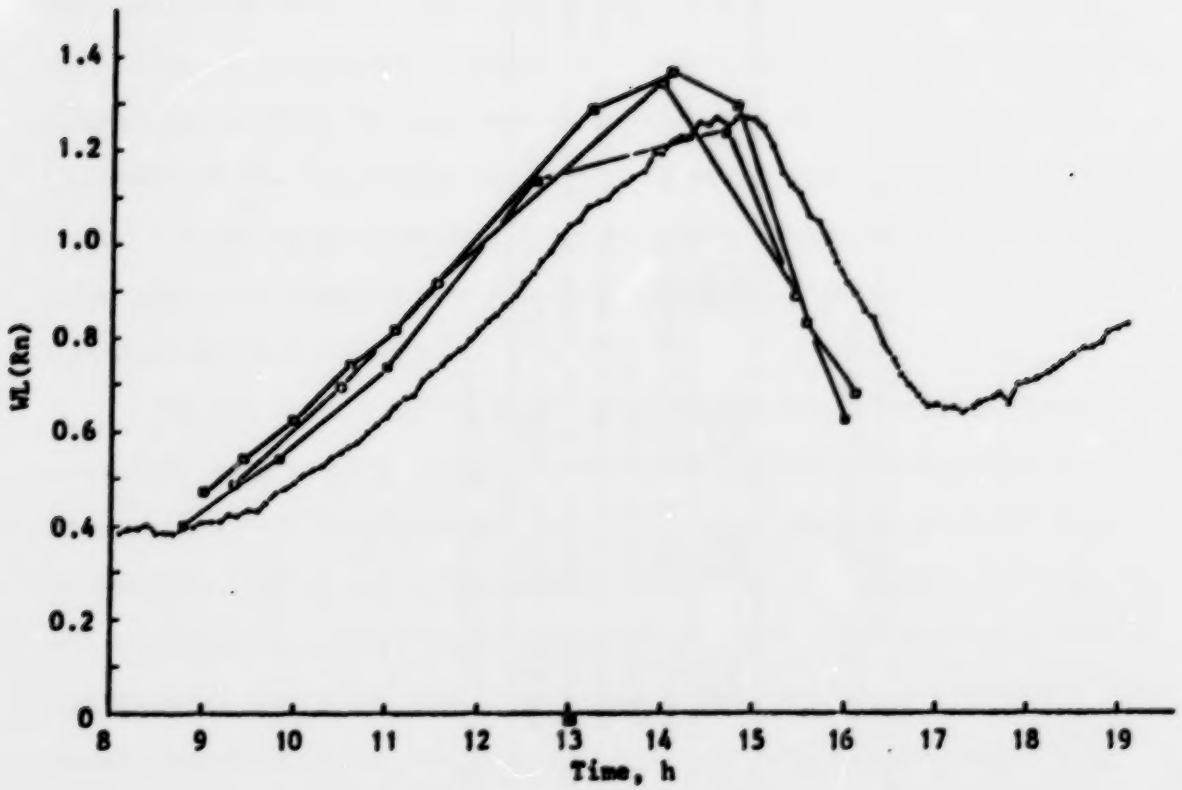

Fig. 2 - WL(Rn) versus time for the WL-1000C (Rn α-spectroscopy, -■-, and Rolle method, -○-), the Markov method, -□-, and the EDA WLM-300 (-··-). Measurements were carried out in a large radon/thoron room (26 m^3).

Figures 3 and 4 show α-spectra from the monitor obtained by feeding the signal from the detector amplifier to an external multichannel analyzer. These tests were conducted to study the spectral purity and resolution of the detector and its associated electronic circuitry, and to investigate plate-out phenomena, particularly for thoron daughters. These tests were done using radioactive sources of the flow-through type manufactured by Pylon Electronics (Models Rn-1025 and Tn-1025), as indicated above. The detector, electronic circuitry and multichannel analyzer were calibrated for α-energy using standard Pu-239, Am-241, Cm-242, RaA, RaC', ThC and ThC' sources, placed at the same distance from the detector as the sampling filter.

Figure 3 shows radon daughter α-spectra (RaA and RaC') from the WLM-300 at two different sampling times. The RaA peak remains essentially the same after a few minutes of sampling because of its short half-life, i.e., an equilibrium is soon reached between the rate of accumulation of RaA and its rate of decay, assuming that all other factors remain constant.

Figure 4 shows thoron daughter α-spectra taken at different times. From the energy calibration of the monitor and Fig 4 one may summarize the following:

1. The peak at channel number $\sim$ 330 corresponds to ThC' deposited on the filter (see curve d);
2. The peak at channel number $\sim$ 210 of curve d, i.e., 3 min after removing the source, and other spectra taken at later times corresponds to ThC deposited on the filter;
3. The peaks appearing at channel numbers $\sim$ 242 and $\sim$ 354 correspond, respectively, to ThC and ThC' deposited directly on the detector, i.e., plate-out. This can be demonstrated by removing the active filter from the sampling head and replacing it by a blank filter and placing another

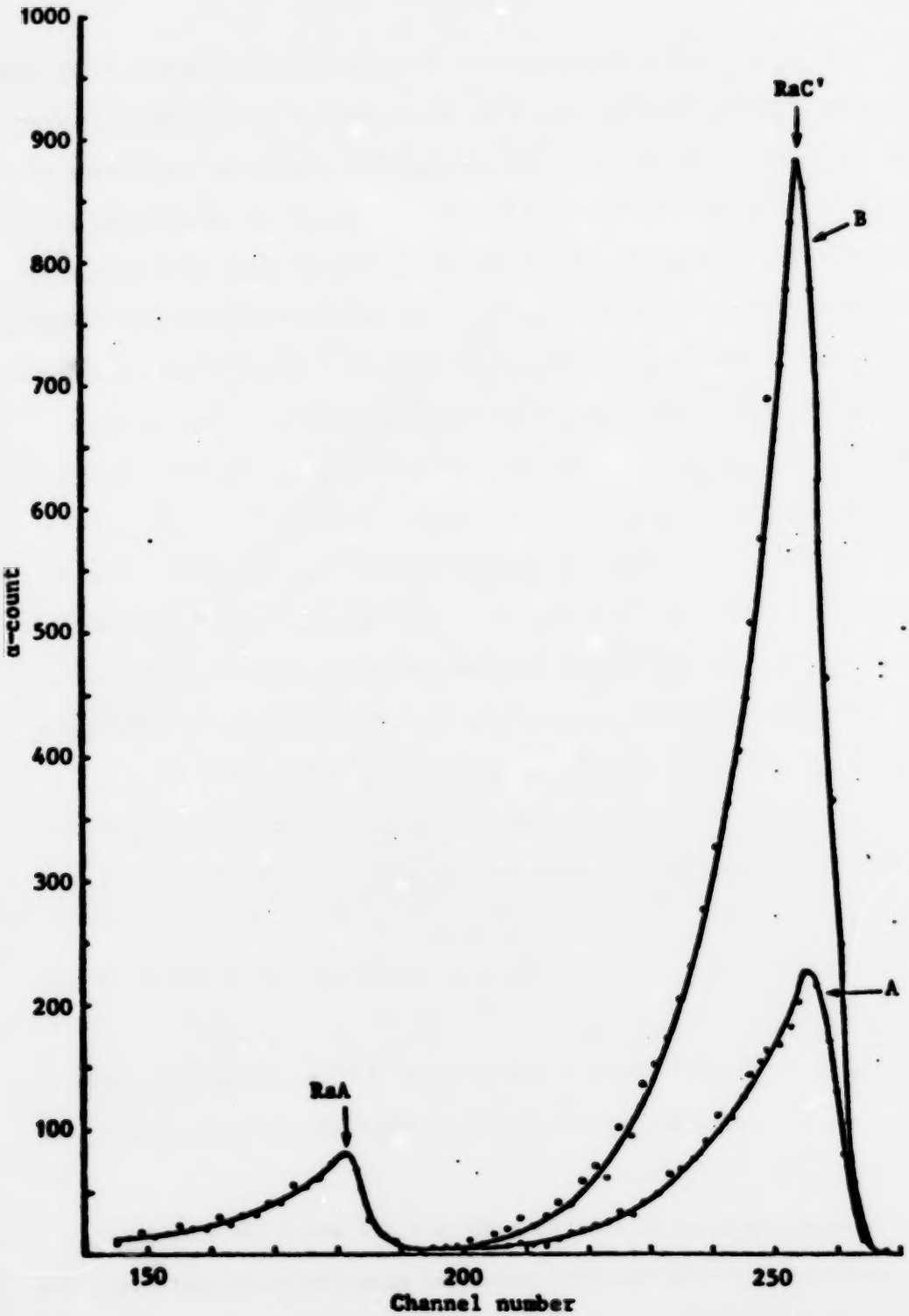

Fig. 3 - Radon daughter spectra (i.e., α-count versus channel number) from WLM-300, using external multichannel analyzer, at two different sampling times: 14 min (curve A) and 74 min (curve B). The RaA peak remains essentially the same because of the short half-life (3.05 min) of RaA.

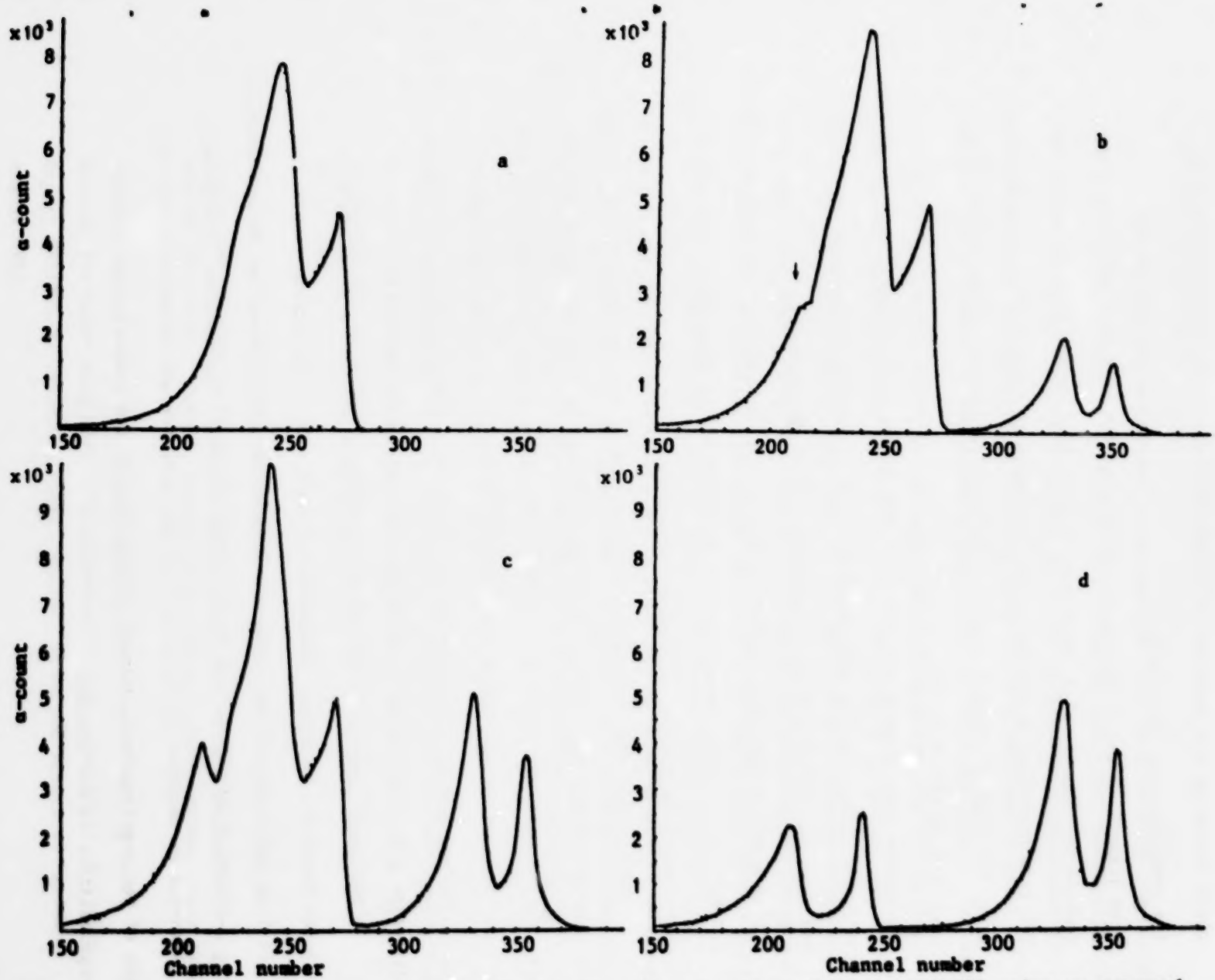

Fig. 4 - Thoron daughter spectra, i.e., α-count versus channel number, from the WLM-300 using an external multichannel analyzer at three different sampling times: 9 min (curve a), 446 min (curve b) and 1421 min (curve c). Curve d represents the spectrum taken 3 min after removing the thoron source.

blank filter on the detector to eliminate α-particles from plate-out on the sampling head (see curve d);

4. From items 1, 2 and 3 one can recognize that the main peak of curve b must contain ThC deposited in the filter (little kink marked with an arrow) and ThC from plate-out in the detector. Furthermore, from α-energy calibration data, the peak at channel number ∿ 268 must correspond to ThA from direct plate-out on the detector;
5. The middle peak between the peak from the filter, now clearly distinguishable in curve c, and the ThA peak from detector plate-out, is composed of Rn-220, ThA from the filter and ThC from plate-out on the detector;
6. Curves c and d show that the energy shifts for ThC and ThC' are approximately 0.7 MeV and 0.5 MeV, respectively. As confirmed by experiment, the energy shift should be smaller at higher α-energies.

Notice that the theoretical contribution of ThA is negligible compared with that of ThB and ThC - this can be demonstrated by substituting half-lives data into the pertinent analytical expressions given above - and hence, it has not been included in the theoretical results of Table A-2. The contribution from Rn-220 has not been included in the calculations because being an inert radioactive gas of molecular size, it is not trapped in the filter.

Previous tests (1 to 3) and the above data indicate a great tendency of thoron daughters to attach themselves to surfaces, a phenomenon complicated by the long half-life of ThB. This can present serious problems to instrumentation using α-spectroscopy and/or time-integrating methods. The problem is compounded by plate-out of daughter products on both the detector and immediately adjacent areas of the sampling head, thereby giving rise to two α-spectra shifted in energy relative to one another.

CONCLUSIONS

The results presented here show that the data obtained with the monitor using a new sampling head with substantially improved plate-out characteristics over an earlier prototype, agree fairly well with grab-sampling measurements. These results are in agreement with radon daughter data obtained by other authors (13). Because of the physical principles on which the monitor is based, its response to fast changes in radiation level is somewhat limited showing a time-lag for radon daughters of at least 1 h. For thoron daughters, the time lag is substantially longer, well over 10 h. Thus, careful consideration to these data, and double-shifted α-spectra effects in the presence of thoron only and/or radon/thoron mixtures, should be given when analyzing experimental data.

The WLM-300 should prove a quite flexible and useful instrument for monitoring underground and surface environments in the uranium mining industry. The memory capabilities of the instrument are particularly noteworthy and its flexibility ideally suitable for experimental and theoretical applications.

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APPENDIX A

Using Equations 2, 4, 8, 9 and 10, and the definitions of WL(Rn) and WL(Tn), the following tables result for C_F(Rn) and C_F(Tn) as a function of the sampling time, T_S, for various radon daughter and thoron daughter disequilibrium ratios (4).

Table A-1 - Theoretical $C_F(Rn)$ as a function of radon daughter disequilibrium ratio and sampling time.

1:X:Y+	cpm++	$\frac{cpm}{WL(Rn)} = C_F(Rn)$	T_s (min)	WL(Rn)*
1:1:1	95.93	9593	30-60	0.0100
	130.10	13010	60-90	
	149.00	14900	90-120	
	159.00	15900	120-150	
	164.00	16400	150-180	
	166.33	16633	180-210	
	167.33	16733	210-240	
	168.00	16800	240-270	
	168.33	16833	450-480	
1:0.72:0.5	61.84	9448	30-60	0.0065
	85.27	13118	60-90	
	98.73	15190	90-120	
	105.71	16261	120-150	
	109.67	16871	150-180	
	111.33	17128	180-210	
	112.00	17230	210-240	
	112.67	17333	240-270	
	113.00	17385	450-480	
1:0.4:0.2	36.34	9563	30-60	0.0038
	49.83	13114	60-90	
	57.87	15228	90-120	
	62.20	16368	120-150	
	64.40	16947	150-180	
	65.57	17254	180-210	
	66.00	17368	210-240	
	66.33	17456	240-270	
	66.66	17543	450-480	
1:0.3:0.15	30.54	9850	30-60	0.0031
	41.33	13333	60-90	
	47.80	15419	90-120	
	51.27	16538	120-150	
	53.07	17118	150-180	
	53.93	17398	180-210	
	54.23	17495	210-240	
	54.67	17634	240-270	
	55.00	17742	450-480	

*$WL(Rn) = 0.00103\ C_{RaA} + 0.00507\ C_{RaB} + 0.00373\ C_{RaC}$

+ $X = C_{RaB}/C_{RaA}$, $Y = C_{RaC}/C_{RaA}$, $1 = C_{RaA}/C_{RaA}$, C_{RaA} = 1 pCi/L

++ is the theoretical cpm, i.e., integrated α-count per unit time interval.

Table A-2 - Theoretical $C_F(Tn)$ as a function of thoron daughter disequilibrium ratio and sampling time

1:k+	cpm++	$\frac{cpm}{WL(Tn)} = C_F(Tn)$	T_s (min)	WL(Tn)*
1:1	99.50	743.2	30-60	0.1339
	164.90	1231.8	60-90	
	229.00	1710.6	90-120	
	292.00	2181.2	120-150	
	353.00	2636.9	150-180	
	413.00	3085.1	180-210	
	470.70	3515.8	210-240	
	526.70	3934.2	240-270	
	581.30	4342.5	270-300	
	633.30	4731.0	300-330	
	686.70	5129.3	330-360	
	733.30	5477.9	360-390	
	783.30	5851.4	390-420	
	830.00	6200.0	420-450	
	876.70	6548.6	450-480	
	1080.00	8067.5	600-630	
	1116.70	8341.4	630-660	
	1150.00	8590.4	660-690	
1:0.6	68.51	530.2	30-60	0.1292
	120.37	931.5	60-90	
	175.10	1355.1	90-120	
	230.67	1785.1	120-150	
	287.67	2226.2	150-180	
	343.33	2657.0	180-210	
	399.00	3087.8	210-240	
	453.67	3510.9	240-270	
	507.00	3923.6	270-300	
	558.67	4323.4	300-330	
	608.00	4705.2	330-360	
	660.00	5107.6	360-390	
	706.67	5468.8	390-420	
	753.33	5829.9	420-450	
	796.67	6165.3	450-480	
	1003.33	7764.7	600-630	
	1040.00	8048.4	630-660	
	1073.33	8306.4	660-690	

Cont. overleaf

Table A-2 - continued

1:k+	cpm++	$\frac{cpm}{WL(Tn)} = C_F(Tn)$	T_s (min)	WL(Tn)*
1:0.4	53.00	417.7	30-60	0.1269
	98.10	773.1	60-90	
	147.90	1165.6	90-120	
	200.60	1580.9	120-150	
	254.30	2004.3	150-180	
	309.00	2435.1	180-210	
	363.30	2863.3	210-240	
	417.00	3286.3	240-270	
	469.30	3698.7	270-300	
	521.30	4108.5	300-330	
	570.70	4497.3	330-360	
	620.00	4886.0	360-390	
	670.00	5280.1	390-420	
	713.30	5621.6	420-450	
	760.00	5989.3	450-480	
	963.30	7591.8	600-630	
	1000.00	7880.7	630-660	
	1033.33	8143.4	660-690	
1:0.2	37.50	301.0	30-60	0.1246
	75.83	608.8	60-90	
	120.87	970.3	90-120	
	170.03	1365.0	120-150	
	221.67	1779.5	150-180	
	274.33	2202.3	180-210	
	327.33	2627.8	210-240	
	380.33	3053.3	240-270	
	432.33	3470.7	270-300	
	483.33	3880.1	300-330	
	533.33	4281.5	330-360	
	583.67	4685.6	360-390	
	626.67	5030.8	390-420	
	676.67	5432.2	420-450	
	720.00	5780.1	450-480	
	923.33	7412.4	600-630	
	963.33	7733.5	630-660	
	996.67	8001.1	660-690	

* $WL(Tn) = 0.1222\ C_{ThB} + 0.01163\ C_{ThC}$

\+ $k = C_{ThC}/C_{ThB}$, $1 = C_{ThB}/C_{ThB}$, $C_{ThB} = 1$ pCi/L

++ is the theoretical cpm, i.e., integrated α-count per unit time interval.

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